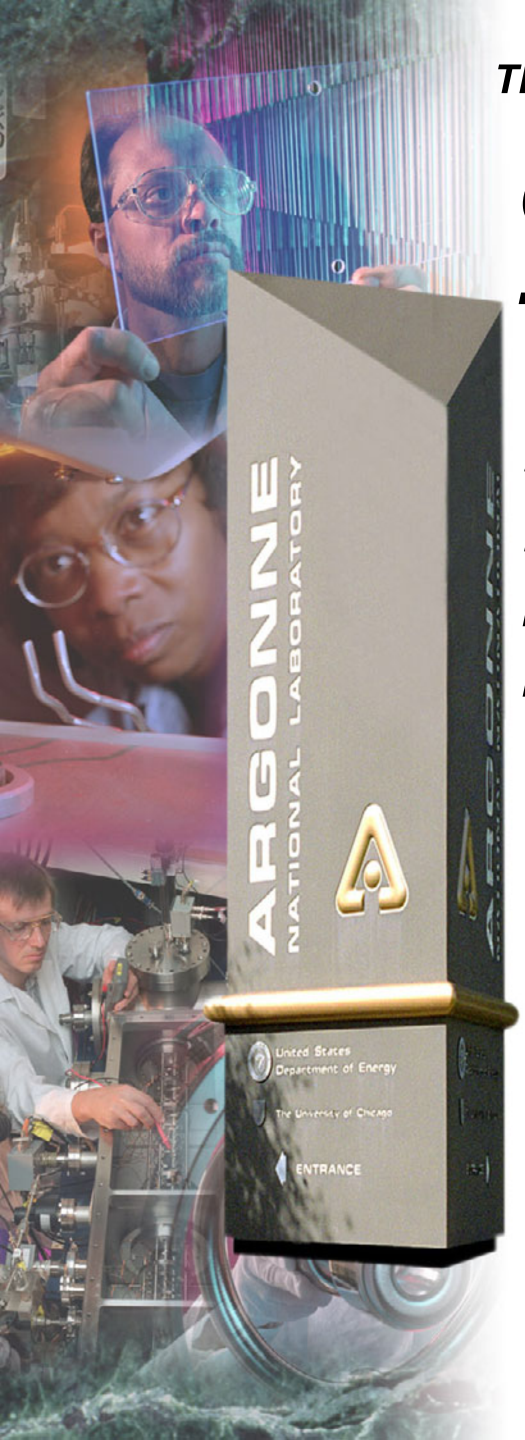

Quick Starting Fuel Processors - A Feasibility Study

2004 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review
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A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Objectives

- **Study feasibility of fast-starting a fuel processor *(FASTER)***
  - To meet DOE targets for on-board fuel processing (FP)
- **Estimate energy consumed (by FP) during start-up**

Relevance : On-board fuel processing will ease the transition to the hydrogen economy

Technical Barrier :

I: FP Startup, Transient Operation

L: CO Clean-up

M: FP Efficiency

Budget : $2.4M

Approach

- **Design, fabricate, and demonstrate the fast-starting capability of a laboratory-scale fuel processor**
  - ATR/WGS/PrOx based design
  - Experimental evaluation at ANL
  - Compare experimental data with model predictions
  - Identify barriers and improvement strategies

- **Collaborative effort with DOE labs and private industry**
  - Component and technical support
    - *LANL, ORNL, PNNL, PCI, AM, QG, university faculty*

- **Model fuel cell system designs to estimate the lifetime (start-up and drive cycle) fuel usage**

Project targets and specifications

Start-up Time	60 seconds
FP Rated Capacity	10 kWe
Start-up Capacity	9 kWe (145 SLPM of H_2)
Fuel	Chevron-Philips Gasoline
Reformate @ 60 sec.	$H_2 > 30\%$; CO < 50 ppm

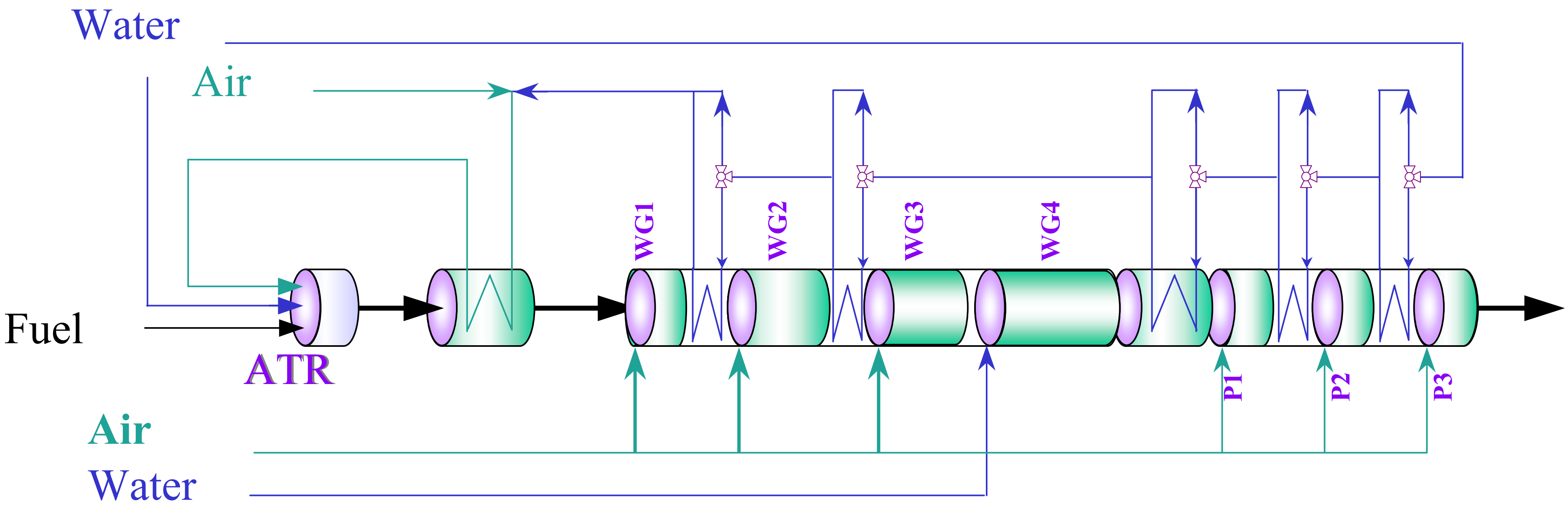
Reviewer Comments

- **… means of ATR ignition have not been adequately considered**
  - Established ATR ignition after testing with liquid/vapor feeds and commercial heating elements
- **Add more schedule time for system optimization after controls testing and total system testing**
  - Capital investments are done, expect to obtain valuable data in the coming weeks and months
- **More detailed control strategies should be investigated**
  - Expect model to enable greater predictive control
- **System design is complicated, too many reactors and HXs**
  - Component and mass reduction opportunities are being explored

Project Safety

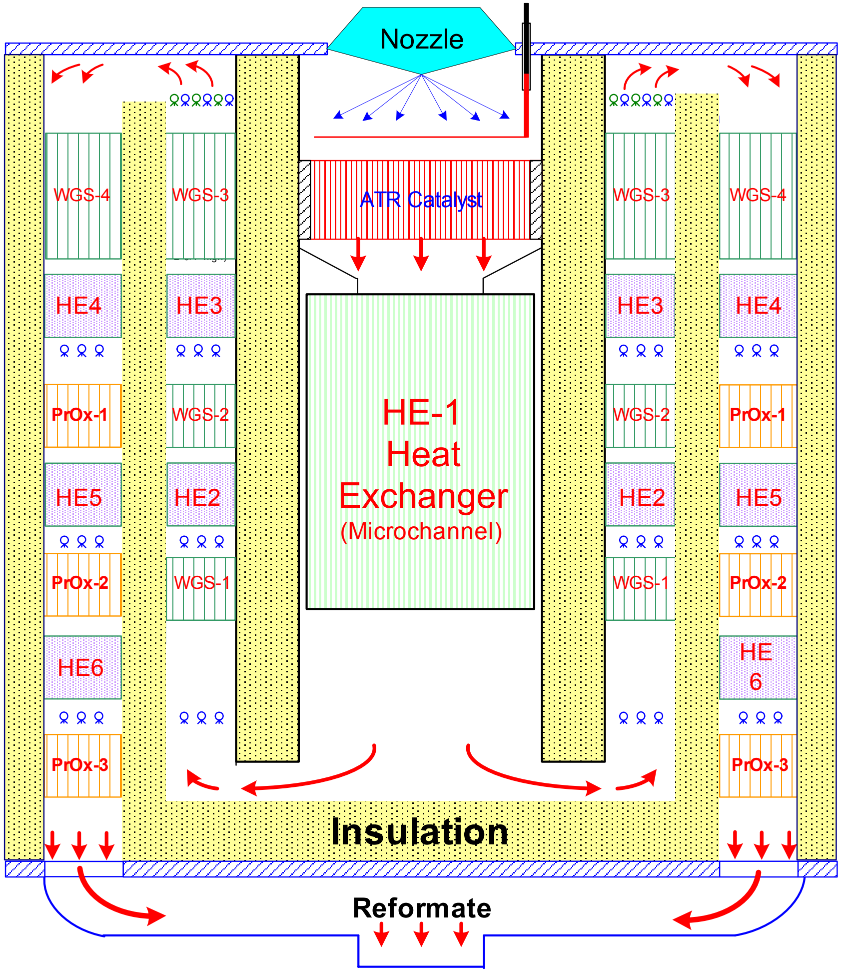
- **Reviewed by committee of scientific, divisional safety, ANL staff (fire, ES&H)**
  - Detailed document includes P&ID, electrical drawings, identification of hazards and mitigation, procedural checklists, and qualified operators
  - Set up in a canopy hood with H_2-sensor and dedicated exhaust
  - Continuously monitor each value (T, P, flow) with automated shutdown triggered at defined alarm condition
  - 3 automated shutdown sequences
    - *Emergency*
    - *Manual soft shutdown*
    - *PC-based normal shutdown*

Start-up Strategy: Produce (H_2+CO) in ATR, oxidize downstream to generate heat



- **ATR is ignited to produce hydrogen**
- **Reformate oxidation in shift zones generate heat for shift reactors**
- **PrOx catalysts are active at room temperature**
  - Active at 25°C, get better as they warm up

Components received from partners were assembled at ArvinMeritor



Components

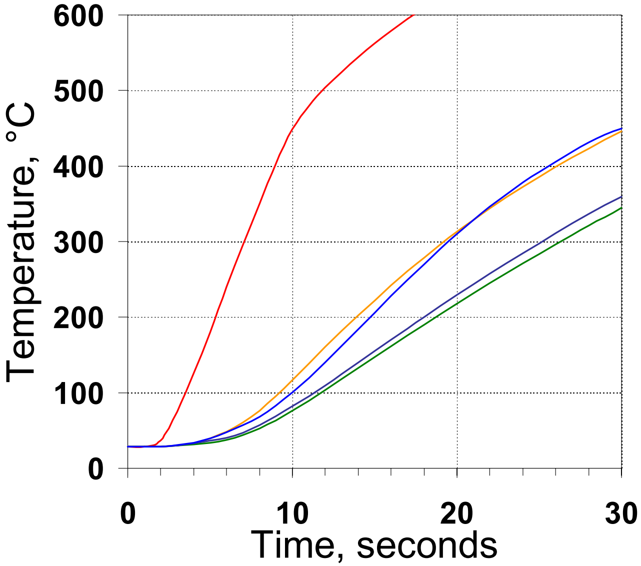
- HE1
  Microchannel HEx- PNNL
- HE2-6
  Foam HEx – ORNL
- ATR
  Microlith™ support – PCI
- WGS
  Microlith™ support – PCI
- PrOx
  Foam support – LANL
- Assembly
  ArvinMeritor

Ignition in the ATR requires appropriate feeds and catalyst temperature

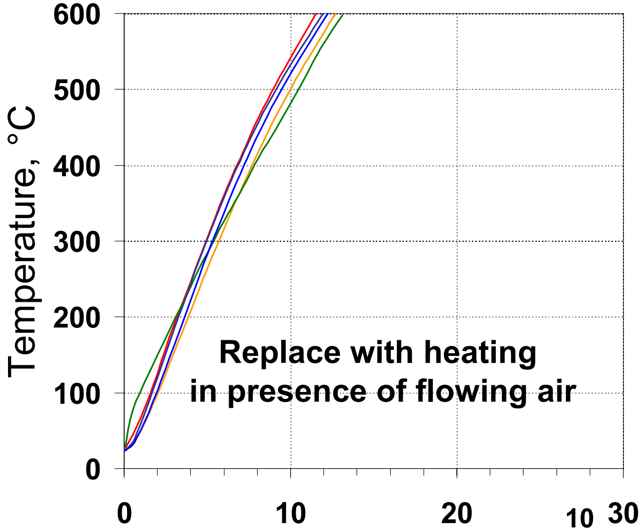
- **Catalyst heated above ignition temperature**
  - Direct heating
    - *catalyst loaded on an electrically-heated support*
  - Indirect heating
    - *by air flowing past a heating element*
- **Fuel injection for POX reaction**
  - Inject fine, uniformly distributed spray of liquid fuel
  - Inject vaporized fuel, premixed at the nozzle
- **Air injection**
- **Water injection for ATR reaction**
  - Inject fine, well-distributed spray of liquid water
  - Inject steam, premixed with air or vaporized fuel

A coiled heater rod was used to preheat the catalyst

- **Coiled heater rod required 25 s to heat catalyst to 300°C**
  - 3 × 400 W

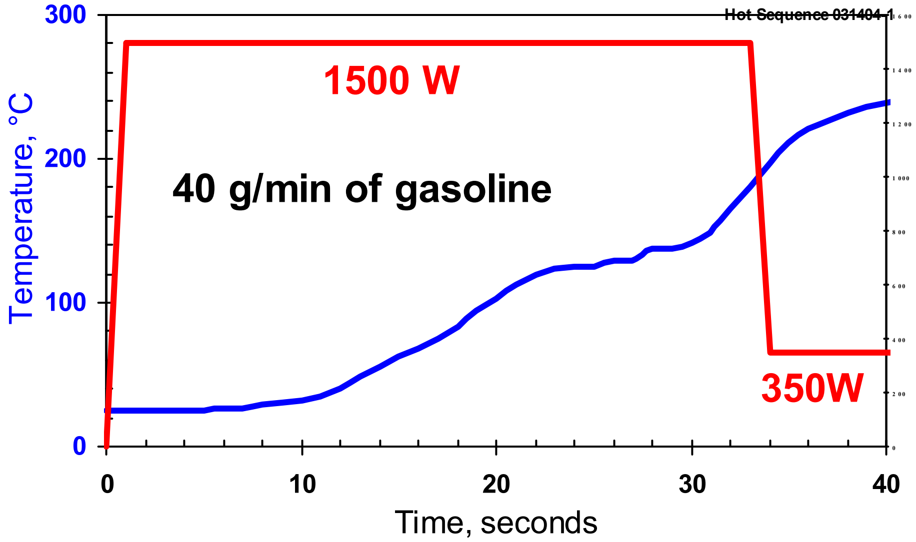


- **Commercial heated support reaches 500°C in 10 s**
  - 12 Volts, 130 Amps, ~1.6 kW
- **Coalesces liquid particles**
  - Should remain powered during liquid water spray
- **Catalyst/support combination needs development**

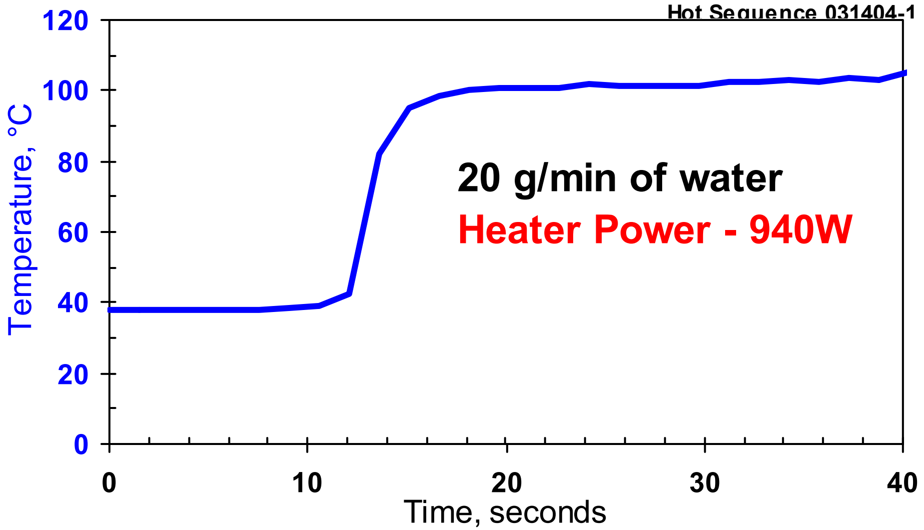


Replace with heating in presence of flowing air

Fuel can be injected into ATR at 30 s



- At 30 s, the exit stream reaches 150°C
- More responsive fuel vaporizer can be designed



- 20 g/min of steam can be available in 20 s
- ATR conditions reduce coking potential, promote shift conversion

ATR start-up tests were done using the central assembly of the FASTER hardware

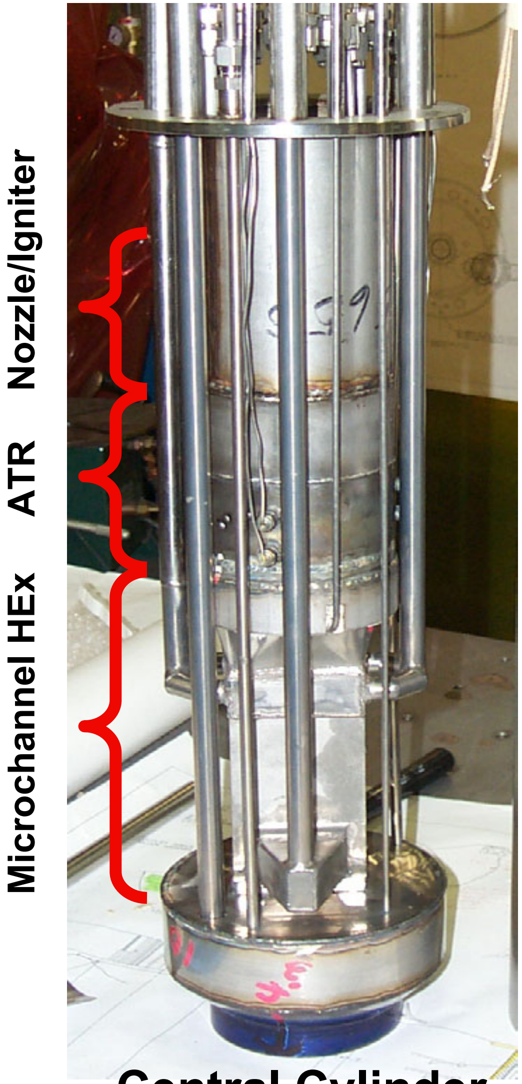
The central cylinder includes

- **Nozzle assembly**
- **Igniter heater coils**
- **Microlith-based ATR (3-layers)**
- **Microchannel HEx**

- **Nozzle assembly permits**
  - Liquid spray injection (fuel and water)
  - Mixing of gaseous streams
    - *Air, vapor fuel, steam*

- **Reformer was started in POX mode:**
  1. (Liquid fuel(a) + air) + liquid water
  2. Vapor fuel(a) + air
  3. (Vapor fuel(a) + air) + steam(b)
  4. (Vapor fuel(a) + air) + liquid water

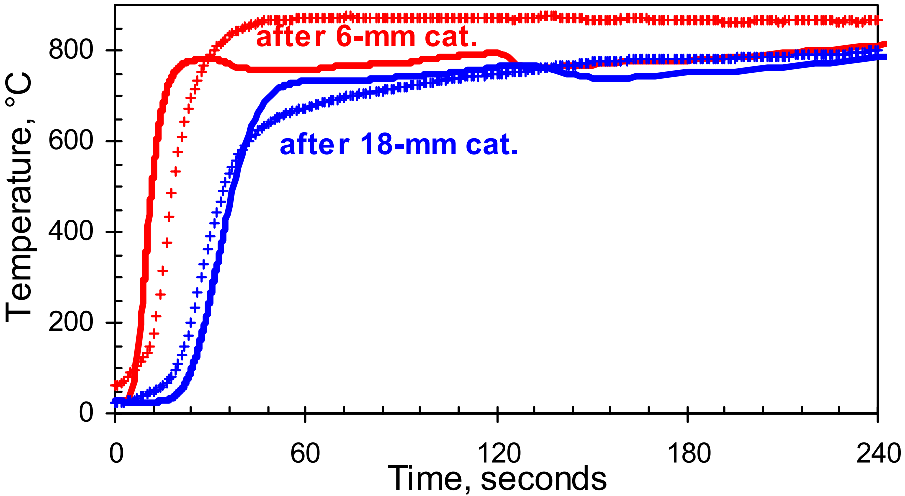
(a) 40 g/min; (b) 20 g/min

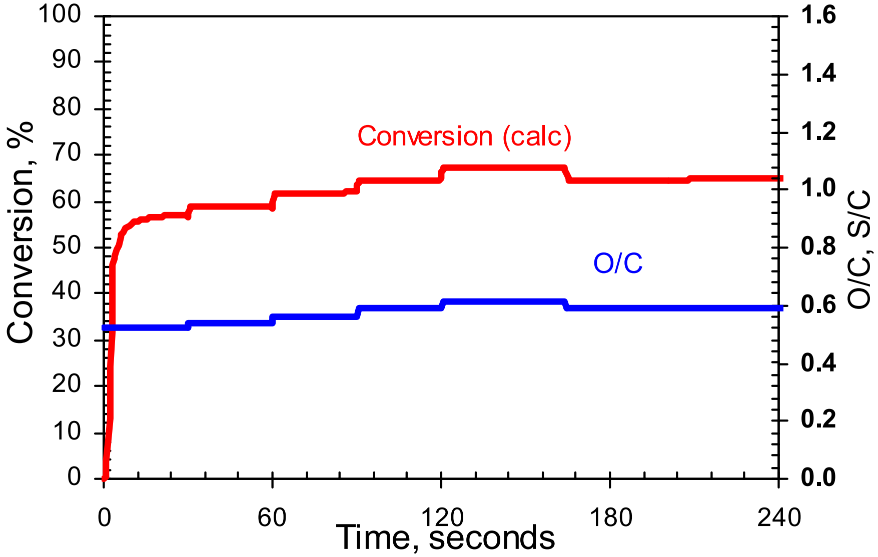


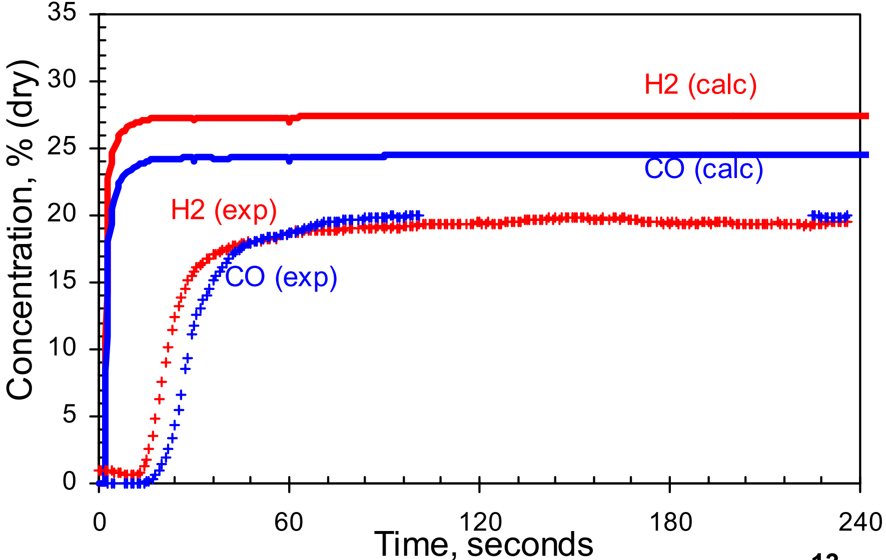
Central Cylinder

CPOX Reforming : 10% H2 available in 22 s

- **Gasoline vapor at 40 g/min**
- **65% fuel conversion at O/C=0.6**
- **700°C in 75 s (at 18-mm depth)**
- **Peak temperature (900°C) limited O/C**
- **H2 concentration exceeds 15% in 28 s**
- **Model under-predicts CH4 yield**
- **CO concentration exceeds 20%**
  - on-line CO analyzer max. is 20%.

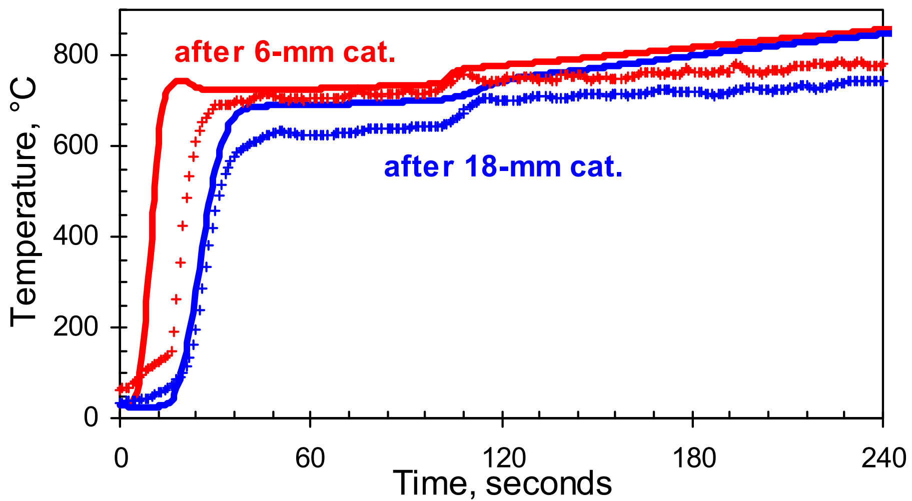


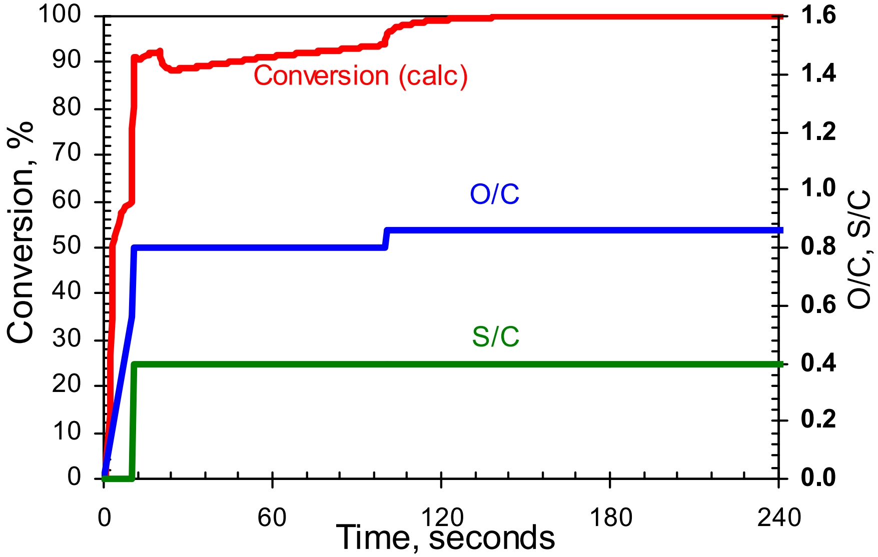


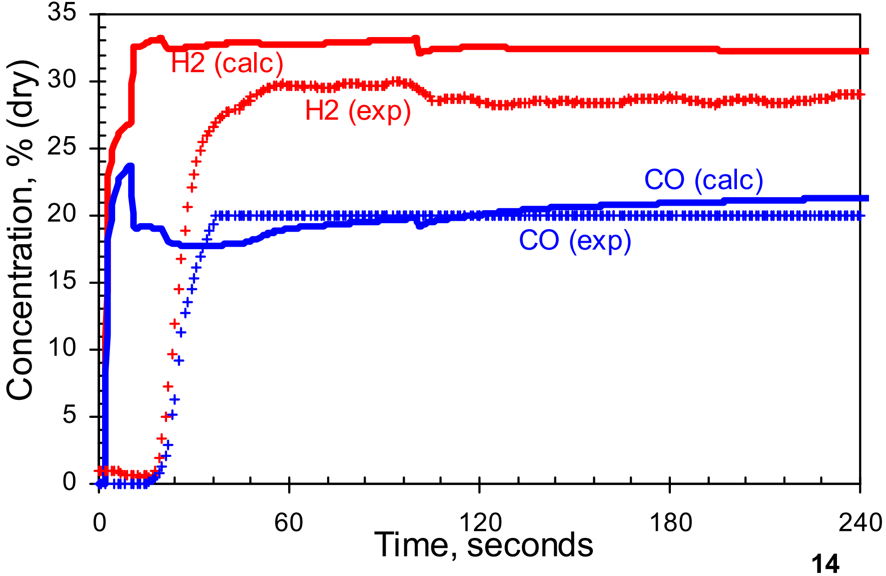


Transition to ATR using steam assists a smooth start-up transition

- 100% fuel conversion at O/C=0.8, S/C=0.4
- Temperature variations between successive layers are smaller than with CPOX
- H2 concentration is higher than with CPOX

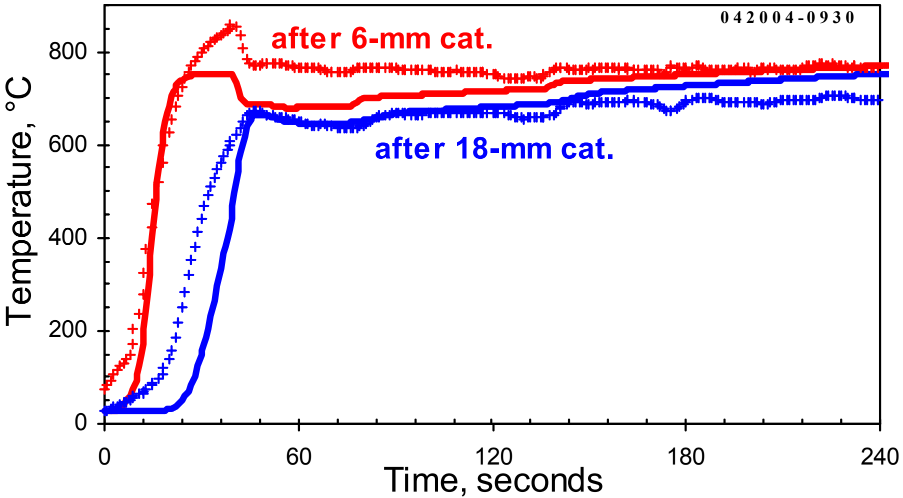


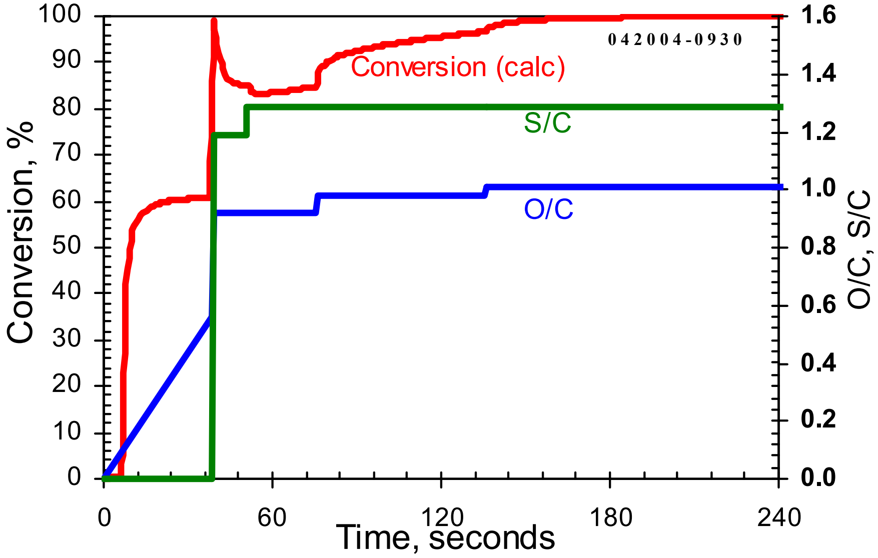


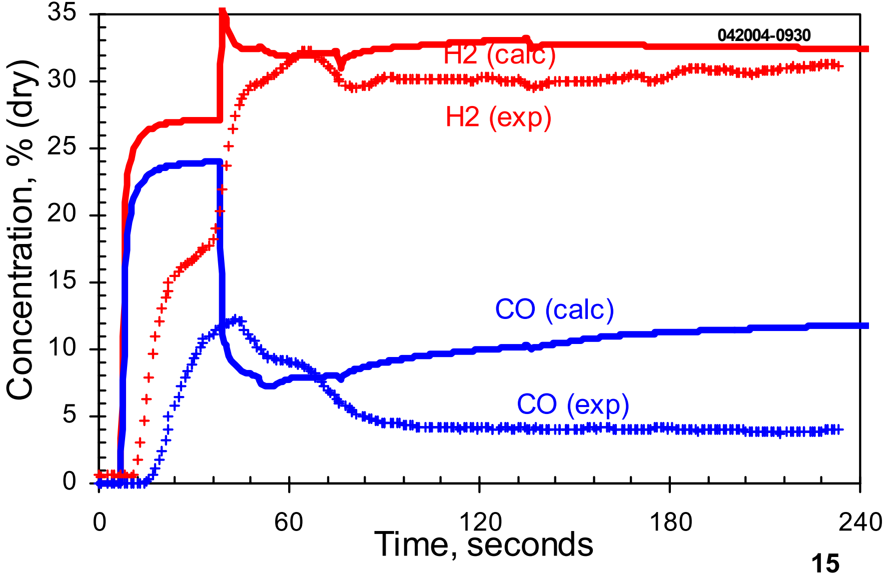


Switching to ATR with liquid water is possible

- **Stability depends on spray size, distribution, and catalyst temperature**
- **Temperature non-uniformities near catalyst inlet edge**
  - General trends are reproducible
- **H2 and CO yields are suitable for oxidation in WGS**
- **Igniter heaters can be turned off**







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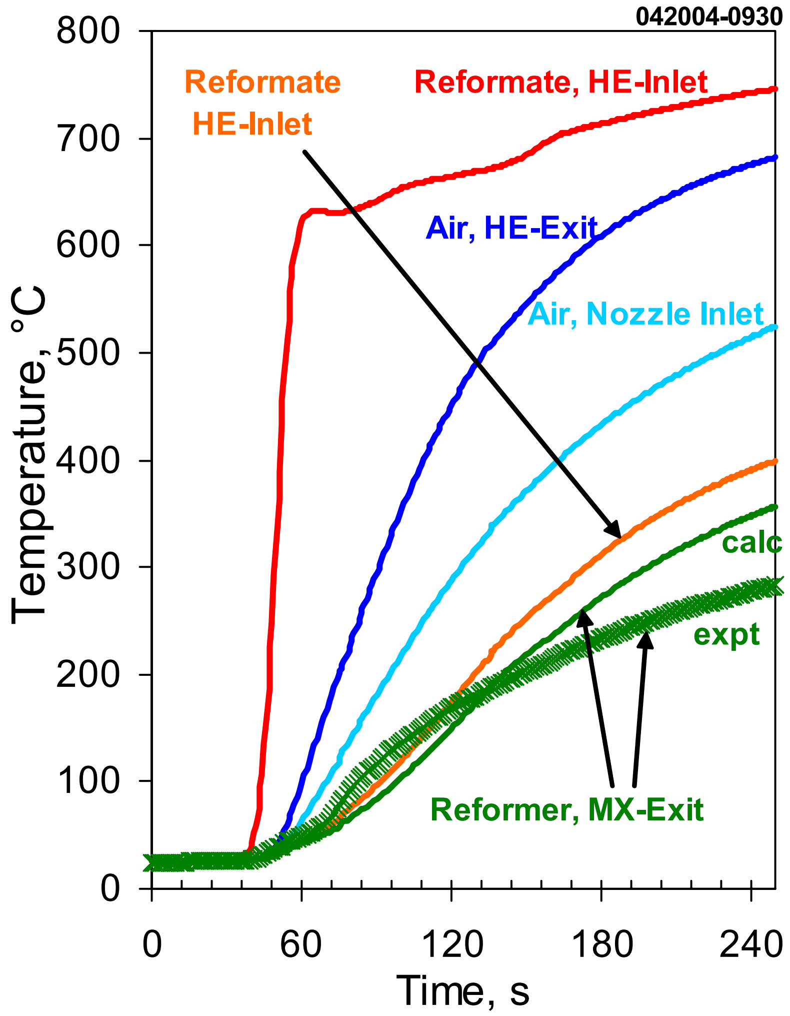
Reformate from HE1 reaches 100°C in 200s

- **At 100°C, the WGS catalyst is expected to support oxidation reactions**
- **Microchannel heat exchanger designed for a heat load of 3.6 kW**
- **Considerable mass contributions from supporting structures**
  - 1988 g for heat exchanger block
  - 737 g for ancillary block
  - 388 g for inlet and outlet tubes



Components fabricated are heavier and will require more start-up fuel than estimates based on functional elements (e.g., catalyst) only

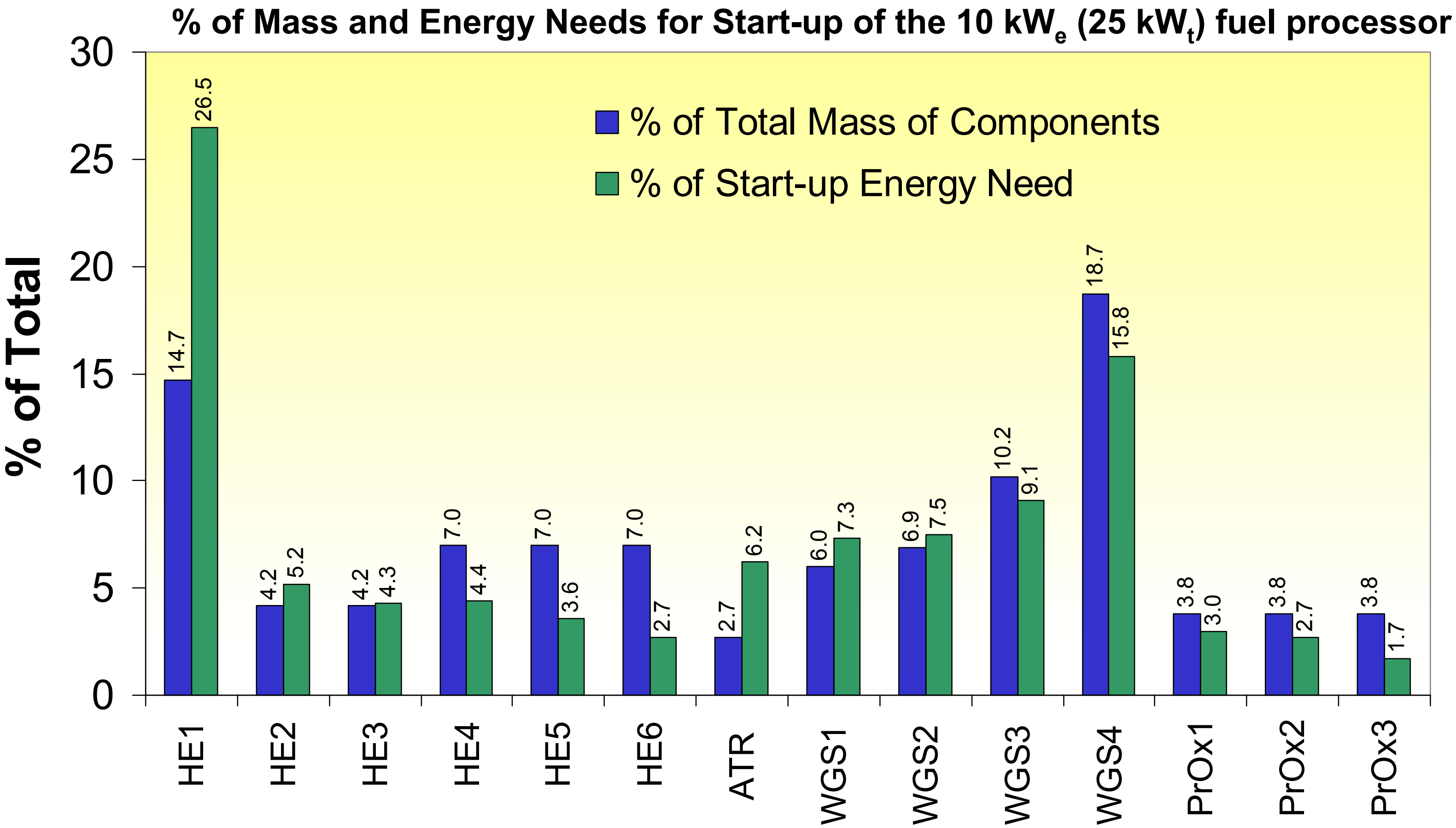
For the 10 kW_e ($25\ kW_t$) fuel processor

Catalysts	ATR	WGS1	WGS2	WGS3	WGS4	PrOx1	PrOx2	PrOx3
Functional Element Wt., g	150	235	375	690	1,150	290	290	290
Component Weight, g	578	1276	1460	2163	3978	800	800	800
Th. Energy Need, kJ	178	210	215	261	454	87	78	48
	Initial Estimate = 430 kJ; Revised = 1531 kJ							

Heat Exchangers	HE-1	HE-2	HE-3	HE-4	HE-5	HE-6
Functional Element Wt., g	1100	586	586	943	943	943
Component Weight, g	3140	898	898	1500	1500	1500
Th. Energy Need, kJ	760	150	124	125	102	78
	Initial Estimate = 654 kJ; Revised = 1339 kJ					

- **Support structures and instrumentation access needs have added to the weights**

Start-up energy needs are dominated by HE1 and WGS4

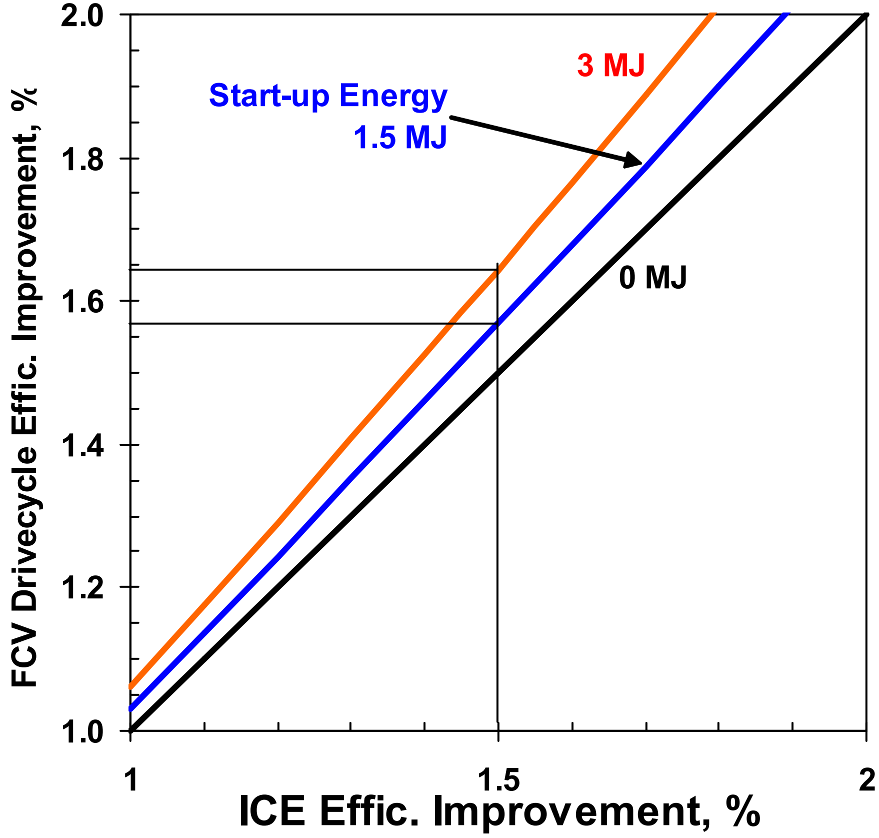


- **The mass of each component is expected to drop with further development**
- **Model indicates that the number of components can be reduced**

Fuel cell vehicles can offer fuel economy better than today's cars

- **Current (ICE) vehicles provide 23.7 mpg (including cold-start)**
- **Operates for 100,000 miles with 10,000 cold-starts**

- **If next generation cars should yield 50% higher mpg (35.6)**
- **A fuel cell vehicle with on-board reformer will have to be more than 50% more efficient than the ICE**



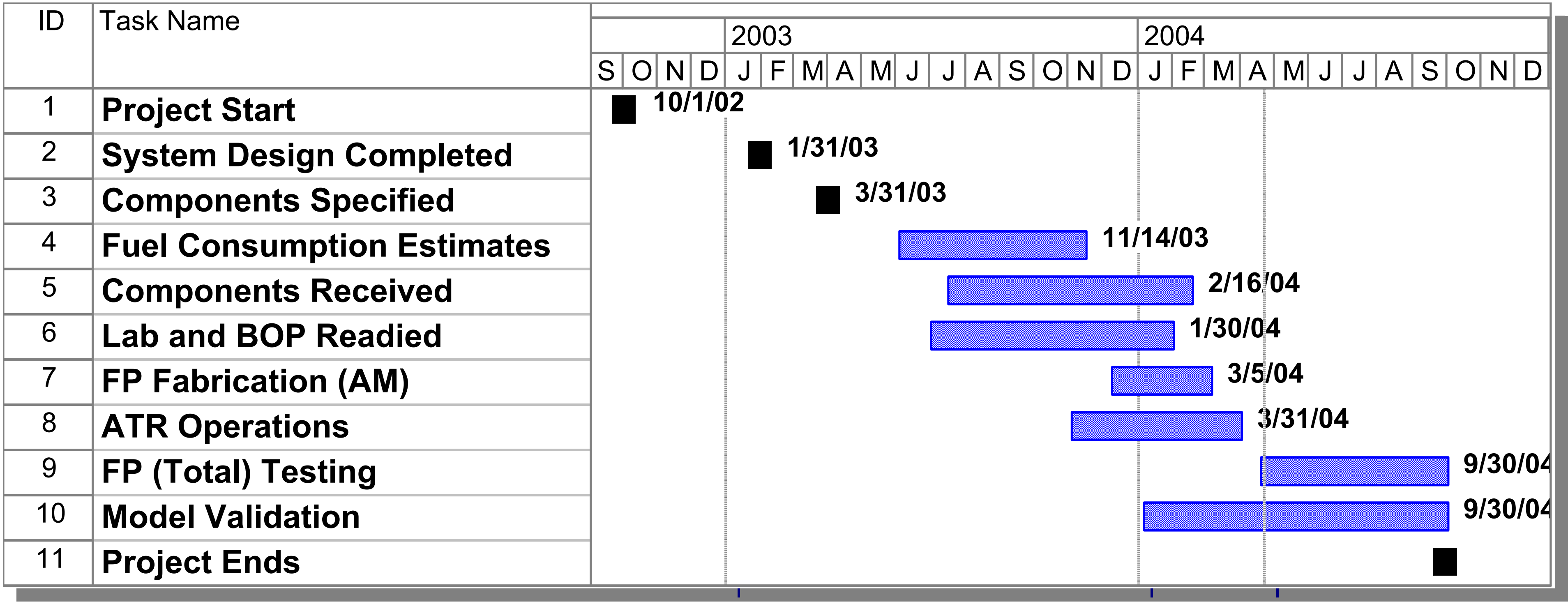
- **If FP consumes 3MJ per cold-start, the FCV will need a drive-cycle efficiency to be 65% higher than the ICE vehicle**
- **Draft DOE target for 50-kWe fuel cell system**
  - 2 MJ per start: 1.5 MJ thermal, 0.5 MJ electrical accessories

Three FP configurations were studied to improve the lifecycle efficiency

- **FP-1 : FASTER design**
- **FP-2 : Compact FASTER design**
- **FP-3 : Integrated with Anode Gas Burner**

	FP-1 (FASTER)	**FP-2**	**FP-3**
Stages of WGS / PrOx / HEx	**4 / 3 / 6**	**2 / 2 / 4**	
WGS Exit CO, %	**1**	**1.4**	**0.4**
FP Drive-Cycle Efficiency, %	**82**	**80**	**78**
Lifecycle Efficiency, %		**73**	**75**
Start-up Energy Consumption, MJ	**7 MJ**	**3.3 MJ**	**1.6 MJ**

Project Timeline



ID	Task Name
1	**Project Start**
2	**System Design Completed**
3	**Components Specified**
4	**Fuel Consumption Estimates**
5	**Components Received**
6	**Lab and BOP Readied**
7	**FP Fabrication (AM)**
8	**ATR Operations**
9	**FP (Total) Testing**
10	**Model Validation**
11	**Project Ends**

Interactions and Collaborations

- **Close collaboration with consortium partners**
  - Components from LANL, ORNL, PNNL, PCI
  - Fabricated at ArvinMeritor
  - Technical support visits, model development support
  - FASTER update meeting, Dec. ’03
  - University faculty participation
  - Private companies contributed significant resources
- **Update to FreedomCar Tech Team, Feb. ‘04**

Accomplishments

- **A collaborative effort has converted a FP concept into experimental hardware**
  - Components received from LANL, ORNL, PNNL, PCI
  - Assembled and fabricated at ArvinMeritor and ANL
  - Test apparatus built and safety approved
  - Set up a flexible data-acquisition and control system
    - *PLC, SCXI based signal processing unit, LabView*
    - *Start-up sequence established for ATR-readiness*

- **Models have supported process design, experiments have validated models**
  - Kinetics established from stand-alone experiments
  - CFD used for component design, data interpretation
  - FEMLAB model to predict steady-state performance and transient response (for control algorithm)
  - GCTool model to design FP system and component sizing

- **Estimated start-up fuel consumption of current FP design**
  - Investigated FP design options that promise improved fuel economy of the FCV

Future Work

- **Accelerate ATR readiness with**
  - Nozzle development
    - *deliver fine, distributed liquid spray*
    - *distribute air uniformly*
  - Catalyst loaded on electrically heated support
- **Revisit reactor configuration for easy access**
- **Further develop control algorithms (with safety interlocks)**
- **Develop catalyst to improve durability, use alternative supports**
- **Reduce thermal mass of fuel processors with focus on lifecycle efficiency**
  - Trade-off with drive-cycle efficiency
  - Significant mass reductions anticipated
    - *reduced number of components*
    - *heat exchanger redesign*

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